SORTING OF SINGLE-WALLED CARBON NANOTUBES USING OPTICAL DIPOLE TRAPS

5   CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   The present application is a continuation-in-part of and claims benefit of priority to U.S. Application No. 10/107,833, filed March 26, 2002.

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BACKGROUND

1.   Field

[0002]   Embodiments of the present invention relate to single-walled
15   carbon nanotubes and, in particular, to sorting single-walled carbon nanotubes.

2.   Discussion of Related Art

20   [0003]   Carbon nanotubes have evoked considerable interest since their

discovery in the early 1990s. Potential uses include everything from

transistors, digital memory, and miniature electron emitters for displays,

to hydrogen gas storage devices for the next generation of environmentally

friendly automobiles.

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[0004]   Typically, a batch of single-walled carbon nanotubes available to

potential users has a mixture of different types of single-walled carbon

nanotubes. For example, in a batch of single-walled carbon nanotubes

there may be metallic single-walled carbon nanotubes and semiconductor

single-walled carbon nanotubes. Within the semiconductor single-walled

carbon nanotubes there may be single-walled carbon nanotubes of

different lengths, diameters, and/or chiralities. Each type of single-walled

carbon nanotube has different properties (e.g., electrical, chemical,

5   optical, mechanical) that are particularly suitable for different

applications. Because they usually come as a mixture not being able to

separate the different single-walled carbon nanotubes can be troublesome

when attempting to utilize a particular type of single-walled carbon

nanotube for a specific application.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0005]   In the drawings, like reference numbers generally indicate

identical, functionally similar, and/or structurally equivalent elements.

15   The drawing in which an element first appears is indicated by the leftmost

digit(s) in the reference number, in which:

[0006]   Figure 1 is a flow chart illustrating process for sorting

semiconductor single-walled carbon nanotubes from metallic single-

20   walled carbon nanotubes according to an embodiment of the present

invention;

[0007]   Figure 2 is a two-dimensional diagram of a hexagonal lattice of a

single-walled carbon nanotube showing the chiral vector and the chiral

25   angle;

[0008]   Figure 3 is a graphical representation showing dielectric susceptibility with respect to resonant frequency;

5   [0009]   Figure 4 is a graphical representation showing electron density of states for a semiconductor single-walled carbon nanotube;

[0010]   Figure 5 is a graphical representation showing bandgap electron density of states for a metallic single-walled carbon nanotube;

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[0011]   Figure 6 is a graphical representation showing the relationship between bandgap and diameter for single-walled carbon nanotubes;

[0012]   Figure 7 is a top view of a microfluidic system according to an

15   embodiment of the present invention;

[0013]   Figure 8 is a flow chart illustrating process for sorting semiconductor single-walled carbon nanotubes according to an embodiment of the present invention

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[0014]   Figure 9 is a top view of a microfluidic system suitable for implementing the process illustrated in Figure 8 according to an embodiment of the present invention;

[0015]   Figure 10 is a top view of a microfluidic system suitable for sorting semiconductor single-walled carbon nanotubes according to an alternative embodiment of the present invention; and

5   [0016]   Figure 11 is a high-level block diagram of a system suitable for using single-walled carbon nanotubes sorted according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

10   [0017]   Figure 1 is a flow chart illustrating a process 100 for sorting semiconductor single-walled carbon nanotubes from metallic single-walled carbon nanotubes according to an embodiment of the present invention. The process 100 will be described as multiple discrete operations performed in turn in a manner that is most helpful in

15   understanding embodiments of the present invention. However, the order in which the operations are described should not be construed to imply that the operations are necessarily order dependent or that they be performed in the order in which they are presented. Of course, the process 100 is only an example process and other processes may be used.

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[0018]   In a block 102, the process 100 determines diameter and chirality (e.g., arm chair, zigzag, helical (or chiral)) corresponding a target class of single-walled carbon nanotubes. A single-walled carbon nanotube can be modeled as a strip of graphite sheet rolled up into a seamless

cylinder with or without end caps. It is "single-walled" because its wall is only a single atom thick. The cylinder is generated when a graphene sheet is wrapped such that an atom on one edge of the sheet coincides with an atom on the other edge of the sheet. The vector pointing from the first

5   atom towards the second atom is called the chiral vector and the length of the "chiral vector" is equal to the circumference of the single-walled carbon nanotube. The direction of the single-walled carbon nanotube axis is perpendicular to the chiral vector.

10   [0019]   Figure 2 is a two-dimensional diagram 200 of a hexagonal lattice of a single-walled carbon nanotube showing the chiral vector and the chiral angle. The chiral vector C_h is defined on the hexagonal lattice as C_h = $n\hat{a}_1$ + $m\hat{a}_2$, where $\hat{a}_1$ and $\hat{a}_2$ are unit vectors, and n and m are integers. The chiral angle θ is measured relative to the direction defined by $\hat{a}_1$. The

15   example diagram 200 has been constructed for (n, m) = (4, 2), and the unit cell of this single-walled carbon nanotube is bounded by OAB'B. To form the single-walled carbon nanotube, imagine that this cell is rolled up so that O meets A and B meets B', and the two ends are capped.

20   [0020]   Different types of carbon nanotubes have different values of n and m. Zigzag nanotubes correspond to $(n, 0)$ or $(0, m)$ and have a chiral angle of 0°, armchair nanotubes have (n, n) and a chiral angle of 30°, while chiral nanotubes have general (n, m) values and a chiral angle of between 0° and 30°. In embodiments of the present invention, scanning

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tunneling microscopy may be used to determine and display atomic structures for single-walled carbon nanotubes.

[0021] Single-walled carbon nanotubes that have different lengths,
5   diameters, and/or chiral vectors have different electronic properties. For example, depending on their chiral vector, single-walled carbon nanotubes with small diameters are either semiconductor single-walled carbon nanotubes or metallic single-walled carbon nanotubes. Metallic single-walled carbon nanotubes may conduct electricity at room
10   temperature. Semiconductor single-walled carbon nanotubes do not conduct at room temperature.

[0022] Referring back to figure 1, in a block 104, the process 100 identifies a resonant frequency of the target class of single-walled carbon
15   nanotubes. In one embodiment, a laser beam emitting a particular frequency of light may be scanned across the mixture of single-walled carbon nanotubes. The electric field component of the light interacts with one or more single-walled carbon nanotubes. The electric field component induces dipole moments in the target single-walled carbon nanotubes.

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[0023] When the frequency of the laser beam is equivalent to a resonant frequency of the target single-walled carbon nanotubes, the induced dipoles in the target single-walled carbon nanotubes will resonate. When the frequency of the laser beam is lower than a resonant frequency of the

single-walled carbon nanotubes, the single-walled carbon nanotubes will be attracted to the laser beam (i.e., optically trapped). When the frequency of the laser beam is higher than a resonant frequency of the single-walled carbon nanotubes, the laser beam will repel the single-walled carbon nanotubes. (When the frequency of the laser beam is around a resonant frequency of the single-walled carbon nanotubes, the optical trapping of single-walled carbon nanotubes is unstable.)

[0024]   The induced dipole moment of the neutral particle in the electric field may be represented by $P = \varepsilon_0 \chi E$. P is the dipole moment per unit volume (or polarization) of the neutral particle in the electric field of the laser beam. ε_0 is the permittivity of free space and is a constant. $\chi(\omega)$ is the dielectric susceptibility of a neutral particle to become a dipole (i.e., to become polarized). The dielectric susceptibility $\chi(\omega)$ depends on the electronic structure of the particle as well as the surrounding medium (e.g., free space, water, etc).

[0025]   Figure 3 is a graphical representation 300 showing dielectric susceptibility χ of a neutral particle (i.e., a single-walled carbon nanotube) to become polarized with respect to laser beam frequency ω. Dielectric susceptibility is a complex function ($\chi(\omega) = \chi'(\omega) + i\chi''(\omega)$), that depends on the frequency ω of the laser beam attempting to polarize it. The graphical representation 300 shows an imaginary part 302 to the dielectric

susceptibility, which is always positive, and a real part 304, which changes sign when crossing a resonant frequency (point 306).

[0026]   The sign of the real part of dielectric susceptibility $\chi'(\omega)$

5   determines whether the single-walled carbon nanotube will be attracted to or repelled from the electric field component of the laser beam. If the sign of the real part $\chi'(\omega)$ is positive, then the laser beam will attract the single-walled carbon nanotube. If the sign of the real part of $\chi'(\omega)$ is negative, then laser beam will repel the single-walled carbon nanotube. The sign of

10   the real part of dielectric susceptibility $\chi'(\omega)$ is determined by the frequency ω of the laser beam. If the frequency ω of the laser beam is lower than the resonant frequency of the single-walled carbon nanotube, then the sign of the real part of dielectric susceptibility $\chi'(\omega)$ is positive. If the frequency ω of the laser beam is higher than the resonant frequency of

15   the single-walled carbon nanotube, then the sign of the real part of dielectric susceptibility $\chi'(\omega)$ is negative.

[0027]   The total interaction system energy U (i.e., the energy that is a product of the dipole moment and the electric field of the laser beam) may

20   be represented by $U = -\frac{1}{2}P \cdot E$, where E is the electric field component of the laser beam. The total interaction system energy U also may be represented by $U = -\frac{1}{2}\varepsilon_0\chi E^2$. The total interaction system energy U thus depends on the sign of the real part of dielectric susceptibility $\chi'(\omega)$ and the intensity of the electric field component of the laser beam E^2. For a

positive $\chi'(\omega)$, U will decrease with increasing laser intensity E^2. Thus, a nanotube with positive $\chi'(\omega)$ will tend to move to an area of higher laser intensity. For a focused laser beam, the intensity distribution is normally Gaussian with highest intensity point at the center of the laser beam,

5   where a neutral particle (i.e. nanotube) with a positive $\chi'(\omega)$ will be most stable (i.e. lowest system energy U). This is the principle of optically induced dipole (optical dipole) traps.

[0028]   Referring back to Figure 1, in a block 106, the process 100

10   determines the relationship between the resonant frequency and the diameter and chirality of the target class of single-walled carbon nanotubes. Figure 4 is a graphical representation showing band structure 400 (energy/γ_0 with respect to density of states (DOS) of single-walled carbon nanotube and graphite; the dotted line represents graphite) for an

15   example semiconductor single-walled carbon nanotube.

[0029]   For example, the semiconductor single-walled carbon nanotube bandgap structure 400 includes several peak pairs that are notated as E_{11}^S, E_{22}^S, etc. These peak pairs are van Hove singularities in the one-

20   dimensional electronic density of states (DOS) for a single-walled carbon nanotube. E_{11}^S is the first energy separation (or bandgap). E_{22}^S is the second energy separation (or bandgap). Each peak pair represents a resonant frequency for the single-walled carbon nanotube. Thus, E_{11}^S represents the first bandgap and the first resonant frequency for the

semiconductor single-walled carbon nanotube and E_{22}^{S} represents the second bandgap and the second resonant frequency for the semiconductor single-walled carbon nanotube.

5   **[0030]**   Figure 5 is a graphical representation showing band structure 500 (energy/γ_0 with respect to density of states (DOS) of single-walled carbon nanotube and graphite) for a metallic single-walled carbon nanotube. The metallic single-walled carbon nanotube bandgap structure 500 also includes several peak pairs that are notated as E_{11}^{M},

10   E_{22}^{M}, etc. E_{11}^{M} is the first energy separation and E_{22}^{M} is the second energy separation. Each peak pair represents a resonant frequency for the single-walled carbon nanotube. Thus, E_{11}^{M} represents the first bandgap and the first resonant frequency for the metallic single-walled carbon nanotube. Note that there are two peak pairs notated as E_{11}^{M}, which may be due to

15   splitting of van Hove singularities caused by trigonal warping effect (i.e., asymmetry near Fermi point in one dimensional electronic structure of the single-walled carbon nanotube).

[0031]   Note also that the metallic peak pair E_{11}^{M} is much larger than

20   the semiconductor peak pair E_{11}^{S} and is even larger than the semiconductor E_{22}. In embodiments of the present invention, scanning tunneling microscopy may be used to determine and display atomic structures and electronic density of states for single-walled carbon nanotubes.

[0032] The energy gaps between the corresponding van Hove singularities are optically allowed inter-band transition energies. The inter-band transition energies are determined by the diameter and chirality of each single-walled carbon nanotube. Figure 6 is a graphical representation illustrating a plot 600 of single-walled carbon nanotube resonant frequencies (i.e., inter-band transition energies) with respect to single-walled carbon nanotube diameter .

[0033] The plot 600 shows the calculated energy separations E_{ii} (e.g., E_{11}, E_{22}, E_{33}, etc.) between van Hove singularities in the one-dimensional electronic density of states (DOS) of the conduction and valence bands for all (n, m) values of considered single-walled carbon nanotube having diameters d_t in the range of approximately $0.4 < d_t < 3.0$ nanometers (nm). The value for the single-walled carbon-carbon energy overlap integral γ_0 is 2.9 eV. The nearest neighbor carbon-carbon distance $a_{C\text{-}C}$ is 1.42 angstroms (Å). The index i in the inter-band transitions E_{ii} denotes the transition between the ith van Hove singularities, with $i = 1$ being closest to the Fermi energy level taken at $E = 0$.

[0034] If Eii is known, then the diameter and chirality of a particular single-walled carbon nanotube can be determined. Note that the bandgap of the single-walled carbon nanotube is inversely proportional to its diameter. For example, in metallic single-walled carbon nanotubes $E_{11}{}^{M} \cong$

6 γ_0 a$_{c\text{-}c}$/d$_t$. In semiconductor nanotubes E$_{11}$^{S} $\cong$ 2 γ_0 a$_{c\text{-}c}$/d$_t$. This means that as the diameter of the single-walled carbon nanotube increases, the bandgap and resonant frequency decreases.

5   **[0035]** Depending on chirality, the inter-band transition energies *Eii* of the single-walled carbon nanotube may deviate from being inversely proportional to the diameter (i.e., may deviate from E$_{11}$^{M} $\cong$ 6 γ_0 a$_{c\text{-}c}$/d$_t$ and E$_{11}$^{S} $\cong$ 2 γ_0 a$_{c\text{-}c}$/d$_t$). As described above, this is due to splitting (in metallic single-walled carbon nanotubes) or shifting (in

10 semiconductor single-walled carbon nanotubes) of van Hove singularities due to trigonal warping effect. This trigonal warping effect happens only if n is not equal m (i.e., armchair single-walled carbon nanotubes).

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[0036] Referring back to Figure 1, in a block 108, a mixture of single-walled carbon nanotubes is disposed in a layer in a microfluidic system. The mixture of single-walled carbon nanotubes includes at least one target single-walled carbon nanotube.

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[0037] Figure 7 is a top view of a microfluidic system 700 according to an embodiment of the present invention. The mixture of single-walled carbon nanotubes in the microfluidic system 700 includes several single-

walled carbon nanotubes 702, 704, 706, 708, 710, 712, 714, and 716. In the illustrated embodiment, the single-walled carbon nanotubes 714 and 716 are target single-walled carbon nanotubes.

5   **[0038]**   The microfluidic system 700 may include one or more layers (two layers 720 and 722 are shown for simplicity, flowing in a direction 732 and 734, respectively) of viscous fluid (e.g., water) flowing smoothly adjacent to each other in laminar flow. In one embodiment, the mixture of single-walled carbon nanotubes may be disposed in the layer 720.

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[0039]   In one embodiment, the width and height of any one of the layers 720 and 722 may be less than approximately one millimeter (mm).

[0040]   The flow of the fluid in any one of the layers 720 or 722 can be
15   characterized by the Reynolds number RN, which is represented by RN = $\rho v d / \eta$, where ρ is the fluid density, v is the fluid speed, η is the viscosity, and d is a geometrical dimensions associated with the flow (e.g., the width and height of the layer). When the Reynolds number is below approximately 2000, the fluid flow is laminar. When the Reynolds number
20   is above approximately 2000, the fluid flow is turbulent.

[0041]   The example microfluidic system 700 also includes a laser beam 730. Referring back to Figure 1, in a block 110, the laser beam 730 is directed at the mixture of single-walled carbon nanotubes. The laser beam

730 may have a frequency that is lower than a resonant frequency of the target single-walled carbon nanotubes. The laser beam 730 induces electric dipoles in the target single-walled carbon nanotubes and traps the target single-walled carbon nanotubes.

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[0042]   In one embodiment, the single-walled carbon nanotubes 714 and 716 are the target semiconductor single-walled carbon nanotubes and the laser beam 730 traps the semiconductor single-walled carbon nanotubes 714 and 716.

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[0043]   Single-walled carbon nanotubes produced using arc discharge, laser ablation, chemical vapor deposition (CVD), or other methods have a certain distribution of diameters. For example, the distribution of single-walled carbon nanotubes made by known high pressure CO disproportionation processes (HiPCO) have diameters that range from approximately 0.8 to 1.3 nm (see area 602). In one embodiment, the energy of the laser beam is chosen below 0.55 eV. In this embodiment, most of the metallic and semiconductor single-walled carbon nanotubes may be trapped because the laser frequency is below the resonant frequency for single-walled carbon nanotubes for E_{11}^M and E_{11}^S (i.e., all of the single-walled carbon nanotubes may be trapped).

[0044]   In an alternative embodiment, the energy of the laser beam is chosen at around 1.05 eV. In this embodiment, most of the

semiconductor single-walled carbon nanotubes are released and all metallic single-walled carbon nanotubes may be trapped because the laser frequency is below the resonant frequency for single-walled carbon nanotubes for E_{11}^M and above the resonant frequency for single-walled carbon nanotubes for E_{11}^S (i.e., traps may be created in only the metallic single-walled carbon nanotubes).

[0045]   In another embodiment, after the metallic single-walled carbon nanotubes are sorted from the semiconductor single-walled carbon nanotubes the energy in the laser beam is tuned between 0.6 – 1 eV. In this embodiment, some semiconductor single-walled carbon nanotubes are released and some semiconductor single-walled carbon nanotubes are trapped because the laser frequency is below the resonant frequency for some single-walled carbon nanotubes for E_{11}^S and above the resonant frequency for other single-walled carbon nanotubes for E_{11}^S (i.e., some semiconductor single-walled carbon nanotubes may be trapped but other semiconductor single-walled carbon nanotubes may not be trapped).

[0046]   In a block 112, the semiconductor single-walled carbon nanotubes 714 and 716 are moved from the layer 720 to the layer 722 and the metallic single-walled carbon nanotubes 702, 704, 706, 708, 710, 712 remain in the layer 720. For example, the focal point of the laser beam 730 may move from the layer 720 to the layer 722. Recall from above that a single-walled carbon nanotube with positive $\chi'(\omega)$ will tend to

move to an area of higher laser intensity, which, for a focused laser beam whose intensity distribution is Gaussian, is at the center of the laser beam. Thus, the movement of the focal point of the laser beam 730 from the layer 720 to the layer 722 may cause the semiconductor single-walled

5   carbon nanotubes 714 and 716 to move from the layer 720 to the layer 722.

[0047]   In one embodiment, a mirror (not shown) may be used to change the position of the focal point of the laser beam 730. For example, the

10   angle of the mirror may be continuously or incrementally changed to change the angle of deflection of the laser beam 730.

[0048]   In a block 114, the process 100 collects the semiconductor single-walled carbon nanotubes 714 and 716 from the layer 722 in one

15   collection place 736 and the metallic single-walled carbon nanotubes 702, 704, 706, 708, 710, 712 from the layer 720 in another collection place 738.

[0049]   For purposes of illustrating an alternative embodiment in which

20   it is appropriate to separate group B semiconductor single-walled carbon nanotubes from a mixture of groups A, B, and C semiconductor single-walled carbon nanotubes. Suppose that a resonant frequency of A semiconductor single-walled carbon nanotubes is higher than a resonant frequency of B semiconductor single-walled carbon nanotubes and a

resonant frequency of B semiconductor single-walled carbon nanotubes is higher than a resonant frequency of C semiconductor single-walled carbon nanotubes.

[0050]   Figure 8 is a flow chart illustrating process 800 for sorting B semiconductor single-walled carbon nanotubes from the A and C semiconductor single-walled carbon nanotubes according to an embodiment of the present invention. Figure 9 is a top view of a microfluidic system 900 suitable for implementing the process 800 according to an embodiment of the present invention.

[0051]   The process 800 will be described as multiple discrete operations performed in turn in a manner that is most helpful in understanding embodiments of the present invention. However, the order in which the operations are described should not be construed to imply that the operations are necessarily order dependent or that they be performed in the order in which they are presented. Of course, the process 800 is only an example process and other processes may be used.

[0052]   In a block 802, the laser beam 930 is tuned to a frequency ω_1 that is lower than the resonant frequency of the B semiconductor single-walled carbon nanotubes and higher than C semiconductor single-walled carbon nanotubes.

[0053]   In a block 804, the mixture of A, B, and C semiconductor single-walled carbon nanotubes is disposed in a first microfluidic layer 920 in laminar flow.

5   **[0054]**   In a block 806, the mixture of A, B, and C semiconductor single-walled carbon nanotubes flows to the laser beam 930 and the laser beam 930 traps the A and B single-walled carbon nanotubes.

[0055]   In a block 808, the focal point of the laser beam 930 moves,
10   which moves the A and B single-walled carbon nanotubes to a second microfluidic layer 922 in laminar flow while the C single-walled carbon nanotubes remain in the first microfluidic layer 920.

[0056]   In a block 810, the laser beam 930 is tuned to a frequency ω_2
15   that is higher than the resonant frequency of the B semiconductor single-walled carbon nanotubes but that is lower than the resonant frequency of the A semiconductor single-walled carbon nanotubes.

[0057]   In a block 812, the mixture of the A and B semiconductor single-
20   walled carbon nanotubes flows to the laser beam 930 and the laser beam 930 traps the A single-walled carbon nanotubes.

[0058]   In a block 814, the laser beam 930 moves the A semiconductor single-walled carbon nanotubes to a third microfluidic layer 924 in

laminar flow while the B single-walled carbon nanotubes remain in the second microfluidic layer 922.

[0059]   In a block 816, the process 800 collects the A semiconductor single-walled carbon nanotubes from the third layer 924 in a collector 926 and collects the B semiconductor single-walled carbon nanotubes from the second layer 922 in a collector 932.

[0060]   Figure 10 illustrates a microfluidic system 1000 suitable for sorting A, B, and C semiconductor single-walled carbon nanotubes according to an alternative embodiment of the present invention. This embodiment may be appropriate when the resonant frequency of the A semiconductor single-walled carbon nanotubes is higher than the resonant frequency of the B semiconductor single-walled carbon nanotubes and the resonant frequency of the B semiconductor single-walled carbon nanotubes is higher than the resonant frequency of the C semiconductor single-walled carbon.

[0061]   The laser beam 1002 may be tuned to a frequency ω_1 that is lower than the resonant frequency of the A semiconductor single-walled carbon nanotubes but higher than the resonant frequency of the B semiconductor single-walled carbon nanotubes. The laser beam 1002 may trap the A semiconductor single-walled carbon nanotubes and move the A semiconductor single-walled carbon nanotubes from the microfluidic layer

1004 to the microfluidic layer 1006 to the collector 1008. The B and C

semiconductor single-walled carbon nanotubes remain in the microfluidic

layer 1004.

5   **[0062]**   The laser beam 1010 may then be tuned to a frequency ω_2 that

is lower than the resonant frequency of the B semiconductor single-walled

carbon nanotubes but higher than the resonant frequency of the C

semiconductor single-walled carbon nanotubes. The laser beam 1010 may

trap the B semiconductor single-walled carbon nanotubes and move B

10 semiconductor single-walled carbon nanotubes from the microfluidic layer

1004 to the microfluidic layer 1006 to the collector 1012. The C

semiconductor single-walled carbon nanotubes may remain in the

microfluidic layer 1004.

15 **[0063]**   The laser beam 1014 may be tuned to a frequency ω_3 that is

lower than the resonant frequency of the C semiconductor single-walled

carbon nanotubes. The laser beam 1014 may trap the C semiconductor

single-walled carbon nanotubes and move the C semiconductor single-

walled carbon nanotubes from the microfluidic layer 1004 to the

20 microfluidic layer 1006 to the collector 1016.

[0064]   It is very common for the batch of single-walled carbon

nanotubes provided by single-walled carbon nanotube manufacturers to

potential users to aggregate together and form bundles similar to ropes

due to very strong van der Waals forces. In one embodiment of the present invention, a batch of single-walled carbon nanotubes may be functionalized prior to sorting using optical dipole traps. For example, the batch of single-walled carbon nanotubes is dispersed in an aqueous

5   surfactant solution to un-bundle them. Suitable surfactants are known (e.g., sodium dodecyl sulfate (SDS)).

[0065]   In one embodiment of the present invention, a tunable laser provides the laser beam. The tunable laser therefore may be able to scan

10   across frequencies or switch among frequencies. In an alternative embodiment, multiple lasers may be used to provide the laser beams. The laser beams may have the same frequency to provide high efficiency trapping of a target class of single-walled carbon nanotubes (i.e., the laser beams may be directed toward the target class of carbon nanotubes

15   simultaneously so that substantially all of the target class of single-walled carbon nanotubes may be trapped in one pass). Alternatively still, the multiple laser beams having the same frequency may be directed toward the target class of carbon nanotubes sequentially so that substantially all of the target class of single-walled carbon nanotubes may be trapped in a

20   serial manner. The laser beam sweeping speed across the microfluidic flows may be fast enough so that all of the target single-walled carbon nanotubes may be removed in one pass.

[0066]   Although for simplicity only one microfluidic system is

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described, in embodiments, several microfluidic systems may be used to sort single-walled carbon nanotubes. For example, two or more microfluidic systems can be implemented in parallel with each other. Alternatively, two or more microfluidic systems can be implemented in series with each other. After reading the description herein, a person of ordinary skill in the relevant art will readily recognize how to implement embodiments of the present invention using two or more microfluidic systems.

[0067] Figure 11 is a high-level block diagram of a system 1100 suitable for using single-walled carbon nanotubes sorted according to embodiments of the present invention. The system 1100 may be a scanning tunneling microscope including a single-walled carbon nanotube tip 1102, a piezoelectric tube 1104 coupled to the control the distance of the tip 1102 from a sample 1106, which is in dotted lines because it is not part of the system 1100, a tunneling current amplifier 1108 to amplify tunneling current from the tip 1102, a control unit 1110 coupled to provide voltage to electrodes 1112 and 1114 on the tube 1104, and a display 1116 to display results of scanning the sample 1106. Scanning tunneling microscopes suitable for using single-walled carbon nanotubes sorted according to embodiments of the present invention are known.

[0068] Other systems suitable for using single-walled carbon nanotubes sorted by bandgap (i.e., optical dipole resonant frequency) according to

embodiments of the present invention include transistor fabrication systems. For example, in many devices transistor bandgap is controlled so that all transistors on a particular device have the same bandgap. This ensures that all transistors have the same threshold voltage. Other

5   systems suitable for using single-walled carbon nanotubes sorted according to embodiments of the present invention include battery manufacturing systems, and fuel cell manufacturing systems.

[0069]   Embodiments of the present invention may be implemented

10   using hardware, software, or a combination thereof. In implementations using software, the software may be stored on a machine-accessible medium. A machine-accessible medium includes any mechanism that provides (i.e., stores and/or transmits) information in a form accessible by a machine (e.g., a computer, network device, personal digital assistant,

15   manufacturing tool, any device with a set of one or more processors, etc.). For example, a machine-accessible medium includes recordable and non-recordable media (e.g., read only memory [ROM], random access memory [RAM], magnetic disk storage media, optical storage media, flash memory devices, etc.), as well as electrical, optical, acoustic, or other form of

20   propagated signals (e.g., carrier waves, infrared signals, digital signals, etc.).

[0070]   The above description of illustrated embodiments of the

invention is not intended to be exhaustive or to limit the invention to the precise forms disclosed. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the embodiments

5   of the invention, as those skilled in the relevant art will recognize. These modifications can be made to embodiments of the invention in light of the above detailed description.

[0071]   In the above description, numerous specific details, such as

10   particular processes, materials, devices, and so forth, are presented to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the embodiments of the present invention can be practiced without one or more of the specific details, or with other methods, components, etc. In other instances, well-

15   known structures or operations are not shown or described in detail to avoid obscuring the understanding of this description.

[0072]   Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, process,

20   block, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification does not necessarily mean that the phrases all refer to the same embodiment. The particular

features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0073]   The terms used in the following claims should not be construed to limit embodiments of the present invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of embodiments of the invention is to be determined entirely by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.